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The Ecology and Acoustic Behavior of Wintering Minke Whales in the Hawaiian and Pacific Islands

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LONG-TERM GOALS

This effort is in support of a long-term goal for better knowledge of marine mammal species densities at U.S. Navy instrumented ranges. By knowing the seasonal densities of various species at a range facility (baseline), one can better understand significance of changes observed from activities such as mid frequency active sonar at that facility.

OBJECTIVES

This effort focuses on Central North Pacific minke whale (*Balaenoptera acutorostrata*), herein referred to as minke whale, vocal behavior while wintering in the Hawaiian Islands observed using bottom hydrophones. The effort is in partnership with the ONR effort with the same title (Norris et al 2009) being headed by Tom Norris of BioWaves leading the field effort and includes participation from SSC PAC (Martin-this effort), University of St Andrews (Janik and Thomas), and the University of Hawaii (Oswald and Nosal).

This specific effort scientific and technical objectives are: 1) Monitor multiple hydrophones to provide near real-time location information for minke whales to an at-sea field team aboard the R/V Dariabar surface vessel; and 2) Conduct analysis of Pacific Missile Range Facility (PMRF) hydrophone data for minke whale acoustics, including signal characteristics, detection, classification, association, localization and density estimation using minke whale boing vocalizations.

APPROACH

The approach is to support the fieldwork by on-site participation at PMRF and conduct subsequent laboratory analysis. The study area includes the Barking Sands Underwater Range Expansion (BSURE) portion of the PMRF facilities. Seventeen bottom-mounted hydrophones (bandwidth ~100Hz to 18KHz) at BSURE (Figure 1) are being utilized for the minke whale study. No organic capability currently exists at PMRF to utilize passive acoustics to detect, classify and localize minke whales. To perform near real-time detection and localization of minke whale boing vocalizations utilizing the hydrophone data requires experienced personnel with appropriate tools. This effort

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14. ABSTRACT
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leverages the Density Estimation of Cetaceans using Acoustic Fixed sensors (DECAF) project being led by Dr. Len Thomas with several co-pi's (Dr. D. Mellinger, Dr. P.Tyack, D. Moretti and S. Martin). DECAF is applying acoustic density estimation techniques to three species of marine mammals on U.S. Navy instrumented ranges as test cases: beaked whales at the Atlantic Undersea Test and Evaluation Center (AUTEC), sperm whales at AUTEC and minke whales at PMRF).

Post fieldwork analysis involves manual acoustic data analysis using Adobe Audition®, a custom tool for review of recorded multiplexed data, and Matlab®. Techniques being developed as part of the DECAF effort for minke whale boing density estimation are being utilized and modified to support this effort. Similarly, findings from this effort are feeding the DECAF case study effort with new information (e.g. the boing frequency feature discovered in this effort helps the DECAF effort associate boings to individuals as discussed later). To detect minke whale boings we are utilizing the strongest component of the boing as observed on PMRF bottom hydrophones. This strongest component is termed the dominant signal component (DSC) and resides in the frequency range between 1350Hz and 1440Hz. Wenz (1964) coined the term "boing" and described the major energy of the Hawaii region boing as being between 1.3kHz and 1.4kHz. A spatially explicit capture recapture technique (SECR) is currently being applied in the DECAF effort for minke whale boing vocalization density estimation (Marques et al 2009). A piece of information still needed for minke whale density estimation is the average boing cue production rate, for which hopefully, this effort can help provide initial information. Acoustic density estimation derived using PMRF hydrophones will be compared to acoustic density estimation utilizing towed hydrophones (Norris effort) allowing comparison of the two different acoustic modality density estimations.

WORK COMPLETED

The field tests in March and April 2009 were fully supported by on-site effort at PMRF. Recordings of the seventeen PMRF BSURE hydrophones were made for the days that the R/V Dariabar was on the PMRF range. Detailed manual analysis of selected data, corresponding to the day of a visual sighting on 27 April 2009, has been completed. Automation of analysis techniques is in progress.

RESULTS

A major accomplishment in FY09 was the development of a process for providing near real-time location cueing for minke whales present on the PMRF range to a field team aboard the R/V Dariabar. While similar cueing of surface craft to marine mammal locations has occurred at the two other U.S. Navy instrumented ranges (AUTEC and the Southern California Off-shore RangE), an automated real time system (the Naval Undersea Warfare Center developed Monitoring Marine Mammals on Navy Ranges) and multiple expert operators are utilized (Moretti et al 2008). PMRF does not currently have a similar system installed. The method developed for localizing marine mammals at PMRF involves use of a custom multiple channel review program (previously developed by SPAWAR Systems Center Pacific) to manually detect boings, associate boings across multiple hydrophones and provide reasonably accurate times of arrival at at least four hydrophones (Martin et al 2009). These times of arrival are then utilized to determine animal location using a hyperbolic localization routine (Vincent 2001).

A significant outcome of the 2009 field work was that the location cues provided by the shore based PMRF effort was a major contributor to the subsequent visual sighting of a minke whale by the field team aboard the R/V Dariabar at 14:00 HST on 27 April 2009. The first VHF radio call with location information of a minke whale was at 10:30 HST while the R/V Dariabar was 23km away from the contact. Several additional localizations of this contact were radioed to the Dariabar over the ensuing 3 hours while the R/V Dariabar transited to the location. At 14:00 HST personnel on the Dariabar sighted a minke whale in the area of the last localizations provided from shore. This is a significant accomplishment given the difficulties, and rarity, of sightings of minke whales in Hawaiian waters. Figure 2 provides a Google Earth® map view of a portion of the BSURE range with a few R/V Dariabar locations along with a subset of minke localizations as determined by the PMRF hydrophones. Another significant accomplishment is what was believed to be an individual minke whale was acoustically tracked for 5 hours and 50 minutes. Collaboration with E. Nosal confirmed the post exercise localizations derived utilizing manually determined arrival times were is good agreement (within a few hundred meters) with model-based localizations utilizing these arrival times.

A significant technical achievement involves new information on the Central North Pacific minke whale boing characteristics as a result of post fieldwork analysis. Specifically, a stable frequency feature of one individual's boings was observed over 5 hours and 50 minutes. This frequency feature, termed the dominant signal component frequency (DSCF), was found to have a mean value of 1384.4Hz (n=54) with a standard deviation of only 1.55Hz (determined using sub-Hertz resolution analysis for the closest hydrophone only). Even more exciting is that other animals, which were readily detected, appear to exhibit similarly stable DSCFs yet with different frequencies (detailed analysis still underway). This has significant impact on the acoustic study of individual minke whales wintering in Hawaii. The DSCF feature is being utilized by the DECAF effort, although using the lower frequency resolution provided by the DECAF minke whale boing detector. This finding raises questions such as: How universal are the stable DSC frequencies? Can the whales voluntarily control this frequency, or is it possibly anatomically controlled (with implications relative to the baleen whale sound production mechanism)?

Figure 3 illustrates the spectral complexity of a typical strong minke whale boing as recorded on hydrophone # 17 at 13:21:58 HST on 27 April 2009. Three strong groupings of the amplitude modulation sideband products (alternatively termed pulse repetition rate harmonic bands) are readily observed clustered around 1.4kHz, 4.5kHz and 8kHz while weaker components are seen, including some over 11kHz. The horizontal range of the animal from this hydrophone was calculated as 6.8km using time difference of arrival techniques. The DECAF developed minke whale boing automatic detector has successfully detected 54 boings from this (suspected) sighted individual from when the recorder was turned on that morning (07:49 HST) until when the minke went quiet at 13:44 HST. Calculation of the inter-boing-interval requires one to have good confidence the calls are from the same individual animal. For this analysis determination was made via the fact that successive calls were of similar energy levels, with similar broadband energy patterns over multiple hydrophones and manual time of arrival based localization of boings from 11:43 to 13:44 HST. The mean inter-boing-interval over the entire 5 hour 55 minute period was 366.746 seconds (n=56) with a standard deviation of 109.3 seconds. This mean interval is in agreement with the six minutes mean reported previously for Hawaiian minke whales (Thompson and Friedl 1982). However, since the amount of time the individual remained quiet has yet to be determined (it has not been reacquired after going silent in recorded data) a meaningful long-term average boing rate for performing acoustic density estimation is still unknown.

Figure 4 provides a high-resolution spectrum (128K pt FFTs, SR=96kHz, 50% overlap, bin width of 0.73Hz, over 2.73 seconds of data) for the signal shown in figure 3. The left pane shows the overall magnitude to over 12kHz. The multiple amplitude modulated sideband products are readily seen (described by Watkins as burst-pulse modulation harmonic bands). The right pane shows a zoom of the DSC component observed at 1384 Hz along with one upper and one lower sideband spaced at the pulse repetition rate of 115 Hz. The vast majority of minke whale boings DSC's observed in data from the PMRF hydrophones resides in the frequency band from 1350 Hz to 1440 Hz. This type of high-resolution spectral analysis was utilized in concert with the DECAF minke boing detector to provide a higher resolution frequency feature (0.73Hz vice the DECAF detectors 5.8 Hz resolution) along with the relative amplitude of the DSC for further investigation.

Automated analysis, using the higher resolution DSCF and relative amplitude features, has just recently been performed for 6 hours 40 minutes of data (07:49 - 14:29 HST) for all 17 hydrophones on 27 April 2009. The DECAF boing detector is capable of detecting very low signal to noise ratio boings (Morrissey et al 2009), and detects 6,075 boings on the 17 phones over this period. This count includes false positives and omits misses, and is felt unmanageable. The high-resolution DSC frequency and relative amplitude features aid in this area. First, by applying amplitude thresholding (>50dB) to reject weaker boings, lowers the total number of detections by 20% to 4,878. Raising the amplitude threshold can be done, however at the expense of detecting the signals on multiple hydrophones which is an important feature for associating boings via the spatial pattern of detections over time. A histogram of the 4,878 amplitude thresholded detection's DSCFs between 1350Hz and 1440 Hz is shown in Figure 5. Three local maxima are clearly seen. The central maximum is at 1384Hz which corresponds to the individual tracked for almost 6 hours and believed to be the individual sighted at 14:00 HST. Two other peaks are seen, one at 1368Hz, and the strongest and widest peak at 1406 Hz (preliminary analysis indicates this strongest DSC frequency peak is the result of two, or more, individual minke whales). One can band pass filter the DSC frequencies and obtain reasonable plots of detections for the 17 phones (vertical axis) vs. time for individuals. Figure 6 shows a 15-minute sample plot of all hydrophones amplitude thresholded detections (top) vs. time while the lower plot shows the DSC frequency filtered (1381.5H-1386.5 Hz) detections. The utility of the DSC frequency filtering is clearly evident and could be utilized for automatic localization, however the current auto detector start time uncertainty is too large and more work needs completed in this area of automation. Other individuals appear to also have fairly constant, yet different, DSC frequencies during this time (e.g. 1368 Hz, 1402.5 Hz, and 1407.5 Hz center frequencies).

Multipath is occasionally observed in hydrophone data and less frequently detected by the autodetector. Figure 7 shows an Adobe Audition® spectrogram (1200Hz to 1500Hz) for twenty seconds of data from hydrophone # 14 at 13:44:20 HST on 27 April 2009. Two boings can be seen; one near the start of the spectrogram and one near the end. One sees the dominant signal components (DSC) between the two added white horizontal lines along with both upper and lower 115Hz PRR sidebands. It is readily discerned in this figure that the first boing has a higher DSC frequency than the second boing. The second boing actually has a DSC frequency of 1384 Hz and is believed to be from the sighted individual. Time differences of arrival techniques utilizing the five closest hydrophones times of arrival (manually determined), locate this individual 23.9km from this hydrophone at this time. Bottom-surface multipath is seen in both boings, the first delayed ~ 1.8 seconds from its first arrival and the second delayed ~2.3 seconds from its first arrival. A ray trace program was utilized to model this situation inputting modeled values (XBT data to 750m from 27 April 2009 with historic sound speed for deeper depths courtesy of Nosal, animal depth of 50m, bottom depth 4550 m, phone depth 4360m, horizontal distance 23.9km to this phone). The bottom depth and sensor depth utilized simulate a sloping bottom for the flat bottom assumption in the ray trace program. Figure 8 illustrates the ray trace output with five eigenrays (direct, surface, bottom, surface-bottom, and bottom-surface paths). Due to the sloping bottom, the bottom and surface-bottom paths show incorrect timing. The modeled direct path distance and arrival time are 24,303.1m @ 16.1683 sec while the bottom-surface path is at 27.409.6m @ 18.2643 sec. The modeled multipath delay for this situation is therefore 2.096 seconds, which is in general agreement with the observed ~2.3 seconds observed in spectrogram data (Figure 7) and first order calculations assuming isovelocity water. The multipath presence is quite interesting as it has implication for single sensors deployed on the seafloor which are much more prevalent in the research community vice the large arrays of hydrophones on U.S. Navy instrumented ranges.

IMPACT/APPLICATIONS

The ability to utilize U.S. Navy range hydrophones at PMRF in Hawaii to cue bio-acoustic field research to minke whale locations has been demonstrated. The discovery of the stability of a detailed spectral component of the complex boing vocalization (the DSCF) contributes new information on minke whale (boing) acoustics and will be investigated further. Presence of bottom-surface multipath is of interest to potential deployment of short to long-term acoustic recorders.

Acoustic density estimation techniques for minke whale boings are currently in development (DECAF), which will enable longer-term investigation of minke density on PMRF by utilizing recorded data from 2002 through present.

TRANSITIONS

The minke whales boing's frequency is being utilized in the DECAF minke test case acoustic density analysis. Work effort will be documented via publication in a peer-reviewed journal.

RELATED PROJECTS

Density Estimation for Cetaceans using Acoustic Fixed sensors (DECAF) is closely related to this effort. Dr. Len Thomas leads the effort at developing, and demonstrating, acoustic density estimation methodology for marine mammals using bottom mounted sensors. Martin is one of the co-investigators on the effort and overseeing the test case for minke whales using acoustic data collected from PMRF in 2006 and 2007. Web site: http://www.creem.st-and.ac.uk/decaf/

An ONR effort with the same title is being led by Thomas Norris (BioWaves). That effort is directed at the at sea field work and towed hydrophone acoustic data.

Pacific Fleet also funds Martin to obtain acoustic data collections for 31 PMRF hydrophones (which includes the BSURE phones) two days per month throughout FY09 with several days of analysis effort included.

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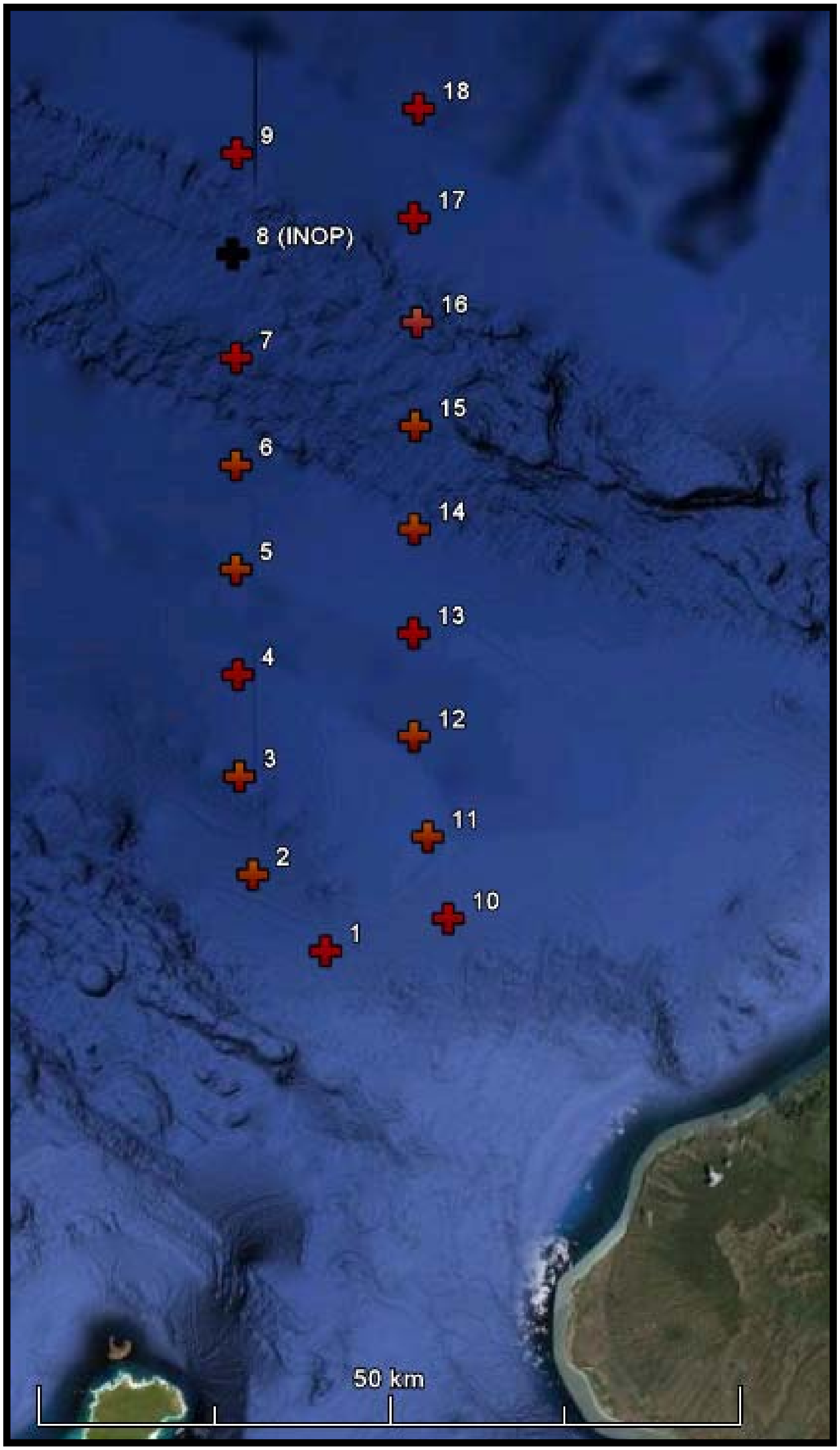

Figure 1 – Study area showing approximate locations of hydrophones at the Pacific Missile Range Facility Barking Sands Underwater Range Expansion area. Water depths range from 1800m to over 4600m. Western Kauai seen at lower right, northern Niihau at lower left.

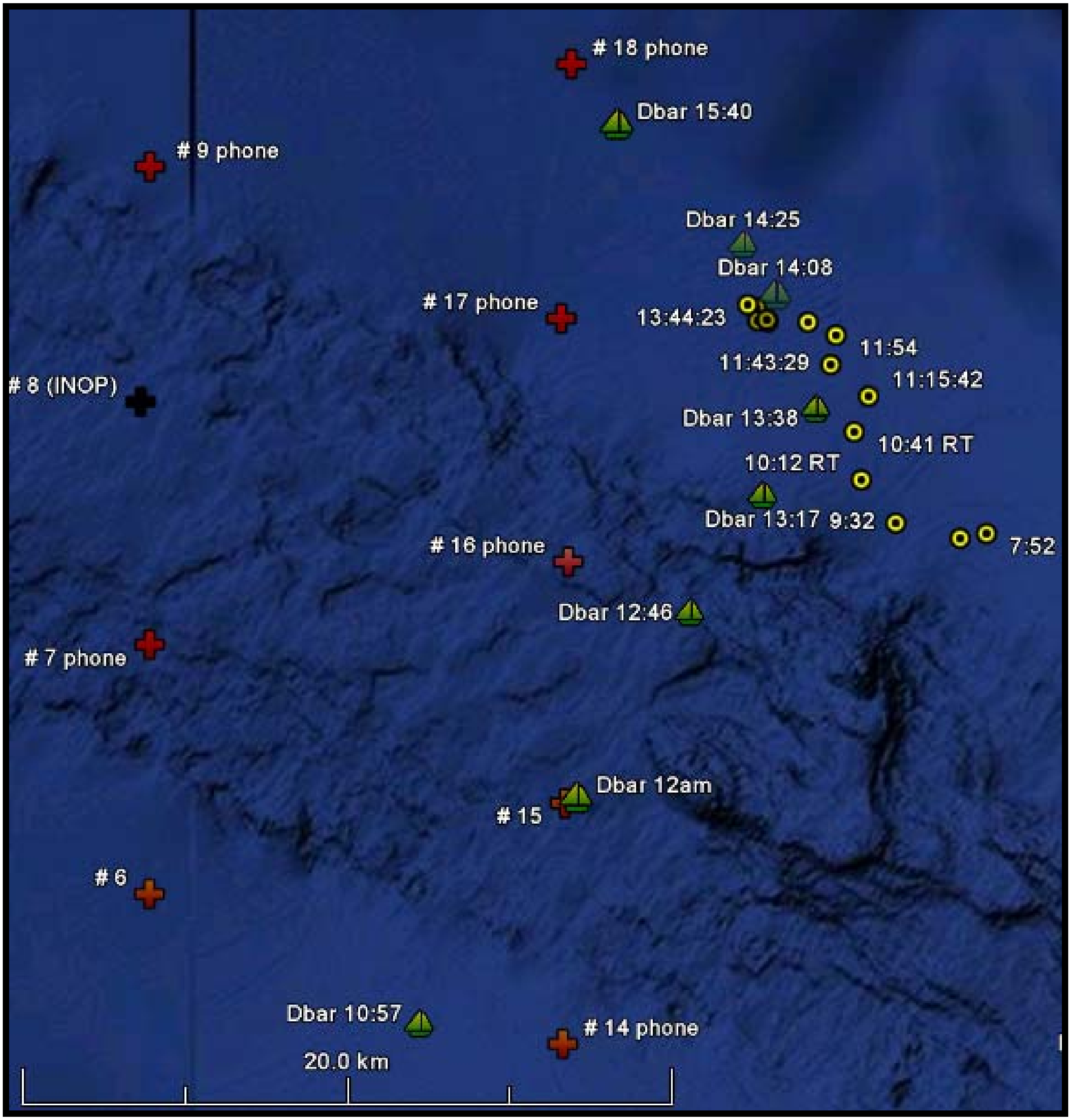

Figure 2 – Overview of 27April 2009 minke whale visual sighting at 14:00 HST by the crew of the R/V Dariabar. Red icons are PMRF hydrophones, green sailboat icons are the R/V Dariabar positions and the yellow dots indicate a subset of minke whale locations determined using PMRF hydrophones. Hawaiian standard times indicated in white next to R/V Dariabar and minke whale locations.

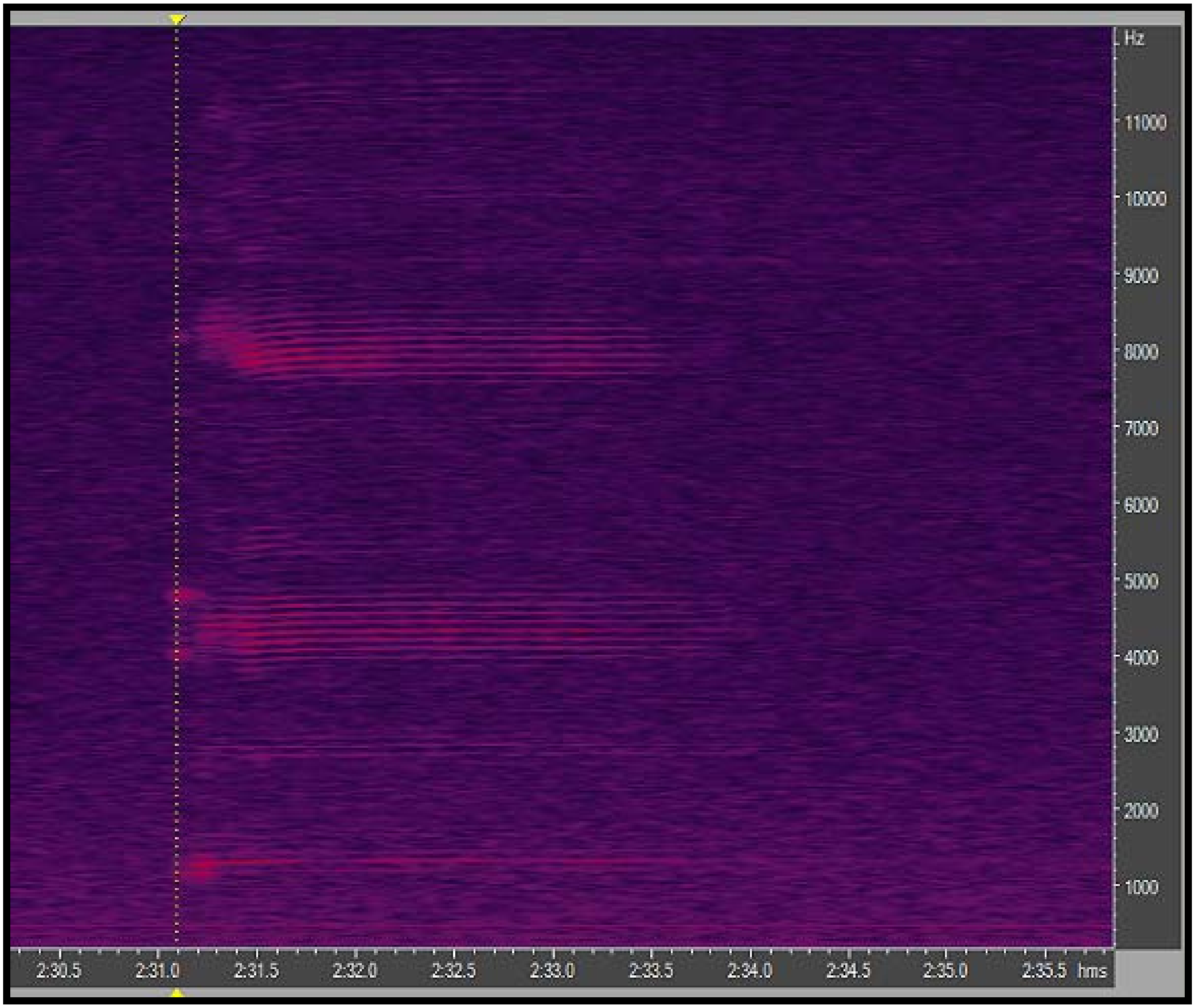

Figure 3 – Spectrogram (DC to 12.2kHz) for a boing received on hydrophone #17 at 13:21:58 HST. The figure shows the spectral complexity of the boing. The horizontal range of the animal from hydrophone # 17 is calculated using arrival time differences to be 6.8km. The three strongest groupings of boing amplitude modulation products (sidebands) are seen at 1.4kHz, 4.5kHz and 8.0kHz. Zooming into this signal allowed 45 separate boing sideband products to be observed.

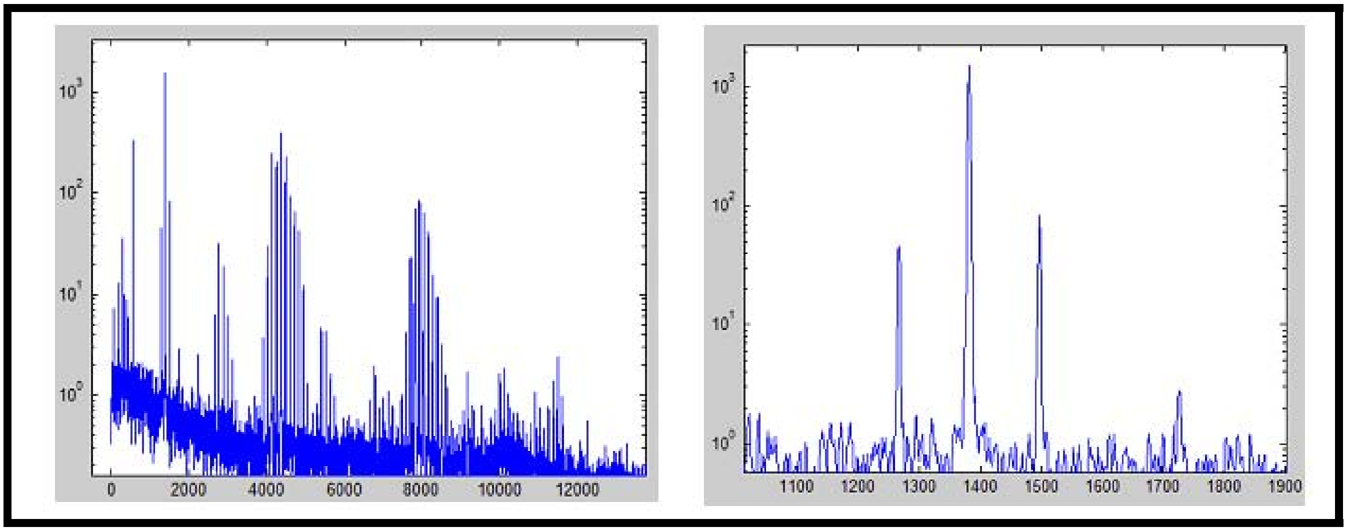

Figure 4 – High resolution spectral view of the same minke boing vocalization shown in figure 2. 128Kpt FFT's averaged over the duration of the boing (50% overlap) of 96KHz sampled data (0.73 Hz bin width). Vertical axis is relative magnitude(log scale). Left – frequency span from 0 Hz to 13 KHz, strongest component is seen to be the 1.384KHz line (termed dominant signal component - DSC). Lines under 1000 Hz are all 60 Hz power related, no discernable line at the pulse repetition rate of 115Hz. Right – enlargement of the 1KHz to 2Khz spectral region showing the DSC and the first 115 Hz upper, and lower sidebands of the DSC.

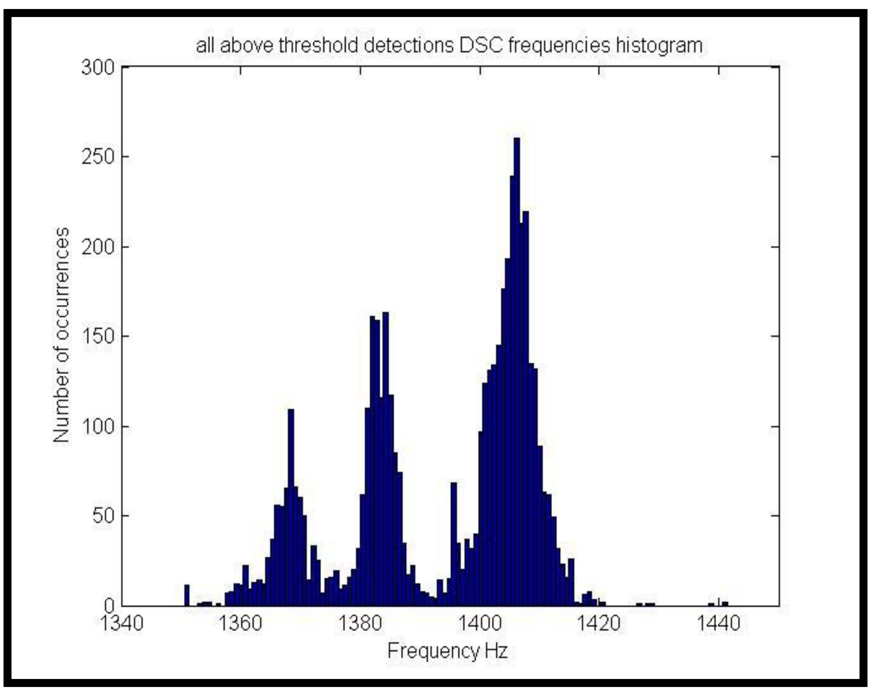

Figure 5 – Histogram of automatically detected DSC frequencies when relative amplitude > 50dB for 6 hrs and 40 minutes of data from 17 BSURE hydrophones 07:49 to 14:29 HST on 27 April 2009. Total number of detections 4,878. The majority of the detections (74%) are from four center frequencies (1368, 1484, 1402.5 and 1407.5Hz) with spans of +/-2.5Hz.

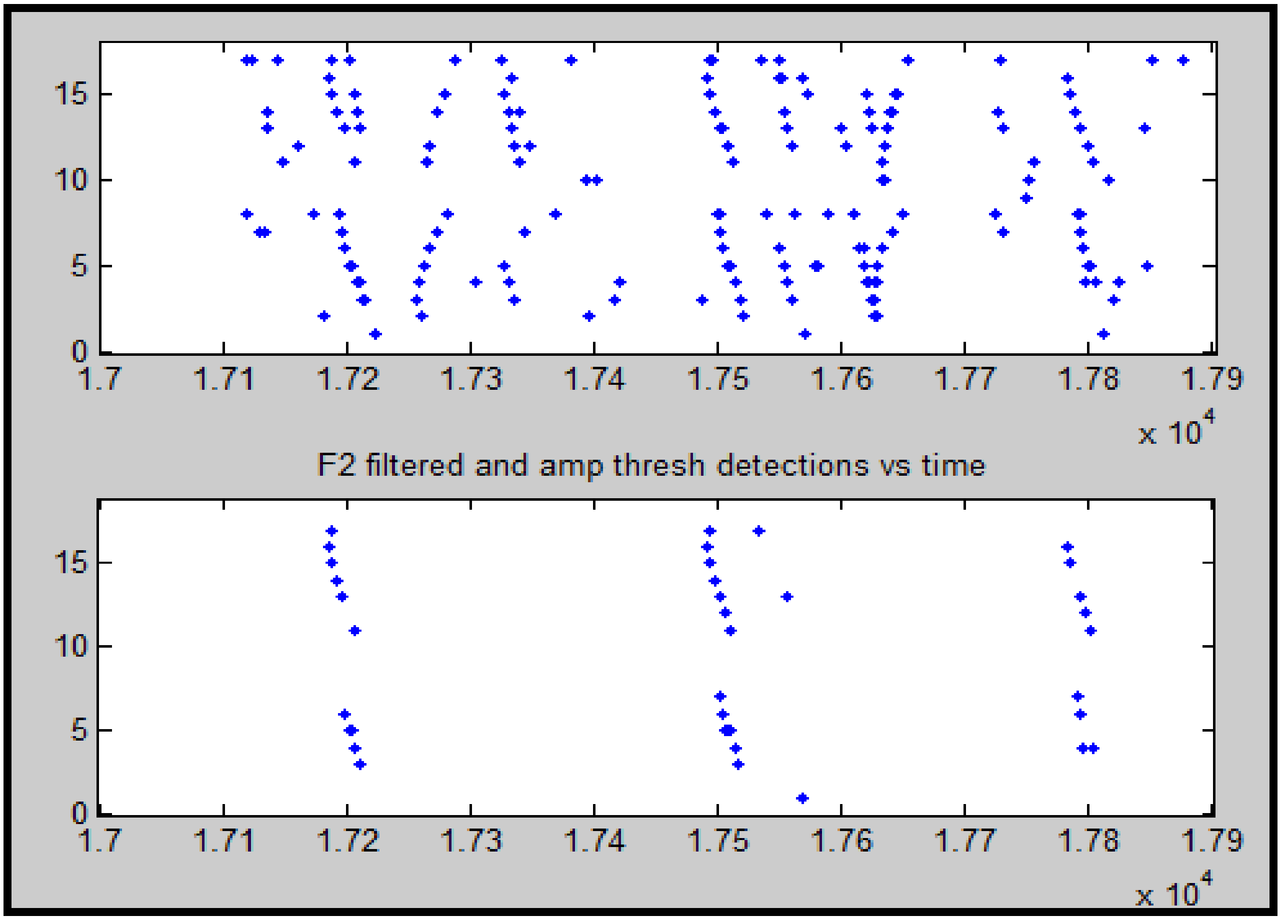

Figure 6 – Fifteen minutes of auto detection data plotted for hydrohphone number (vertical axis) vs. time in seconds (horizontal axis). Upper plot shows all detections > 50dB relative amplitude. Lower plot shows only detections with dominant signal component between 1381.5Hz to 1386.5 Hz. Three boings are clearly seen at times 1.72, 1.75 and 1.78 x10^4 seconds. As can be seen, up to a dozen of the 17 hydrophones can detect a single boing, the curved pattern seen below is a result of the sound propagating throughout the range over tens of seconds.

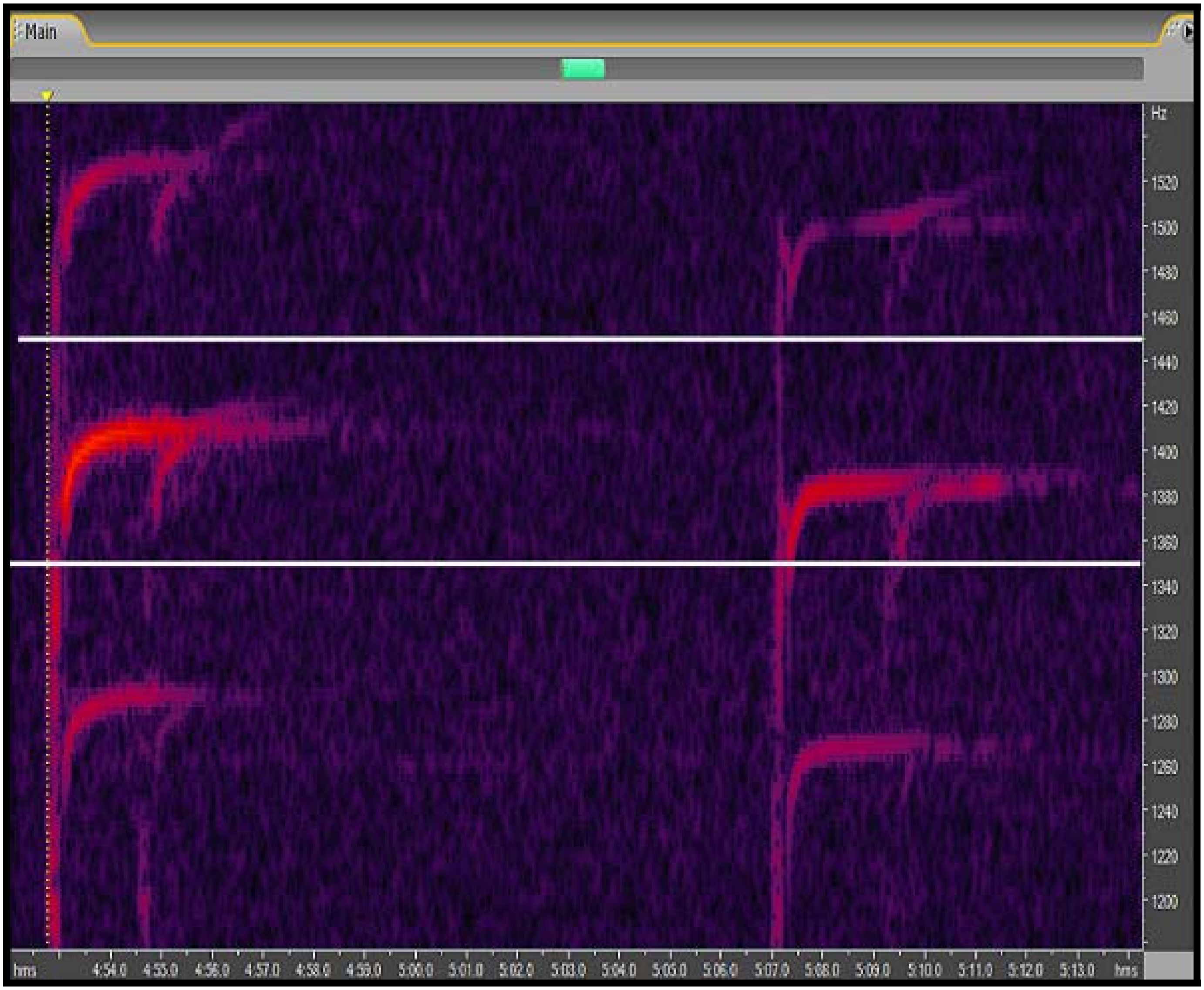

Figure 7 –Twenty second spectrogram (1180Hz to 1550Hz) of two boings received on hydrophone #14 at 13:44 HST on 27April 2009. The two horizontal white lines indicate the band of 1350Hz to 1450Hz. The first boing on the left is a relatively strong signal from a Minke whale in the southern end of the range, with a dominant signal component frequency, (DSCF) of ~ 1410 Hz. The second signal to the right is the last boing detected at 13:44:20 from the sighted individual, which exhibits the 1384Hz DSCF. Upper and lower sidebands from the 115Hz pulse repetition rate are also clearly seen for both boings. Each boing exhibits a time delayed multipath, believed to be bottom-surface multipath arrivals delayed by ~ 1.8 seconds for the first boing, and ~2.3 seconds for the seconds boing. The short multipath delays are indicative of long propagation ranges (>20Km).

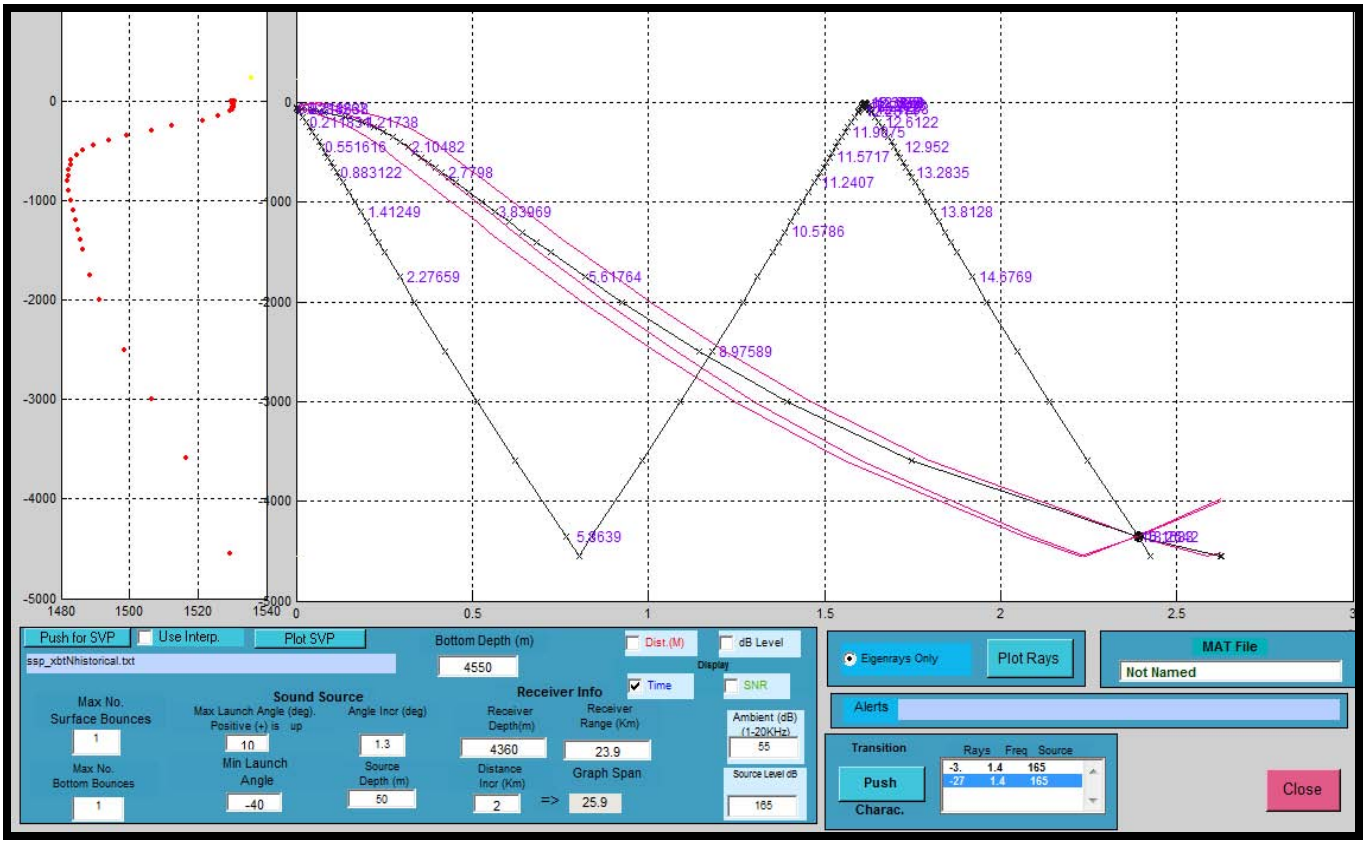

Figure 8 – Ray trace program results for modeled animal depth of 50m, bottom depth of 4550 m, hydrophone depth of 4360m, horizontal range 23.9km, sound speed 0-700m from XBT data 27 April 2009 combined with historical deeper data (courtesy Nosal). Five eigenrays found (direct, surface, bottom, surface-bottom and bottom-surface). The delay for the direct to bottom-surface path for this case is 2.1 seconds which is in general agreement with the ~2.3 seconds observed in spectrogram data (figure 7).